



## **Cost and Performance Report: Low-Hazardous Air Pollutant (HAP)/Volatile Organic Compound (VOC)-Compliant Resins for Military Applications**

**by John La Scala, Steven Boyd, Kevin Andrews, Terese Glodek, Caroline Lochner, Philip Myers, Felecia Levine, Daniel De Bonis, Robert Hayes, James Sands, Maureen Foley, Roger Crane, Nicholas Shevchenko, Steven Andersen, John Gillespie, Jr., David Fudge, Kyle Brand, Michael Starks, Jorge Gomes, Lawrence Coulter, Kenneth Patterson, Dane Morgan, Frank Bruce, Xing Geng, and Giuseppe Palmese**

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# **Army Research Laboratory**

Aberdeen Proving Ground, MD 21005-5069

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<p>Liquid resins used for molding composite structures are a significant source of hazardous air pollutant (HAP) emissions. One method of reducing styrene emissions from vinyl ester (VE) resins is to replace some or all of the styrene with fatty acid-based monomers. This patented technology allows for the formulation of high-performance composite resins with no more than 25 weight-percent styrene, which is a 25%–50% reduction in HAP emissions vs. commercial VE resins. This work validated the commercially produced low-HAP vinyl ester resins from Applied Poleramics, Inc., for use in U.S. Department of Defense composite structures. Tests have shown that the established resin formulations met the property requirements, including viscosity, glass transition temperature, modulus, strength, short beam shear strength, fracture toughness, and weatherability. The Army has demonstrated and validated the use of the high-mobility multipurpose wheeled vehicle transmission container, M35A3 hood, and M939 hood under laboratory testing and field conditions. The Air Force has demonstrated the production of an F-22 canopy cover, T-38 dorsal cover, and rapid prototyping splash molds. Mine countermeasure rudders were successfully demonstrated at production level and validated at the laboratory level. An economic analysis has shown that these resins will cost an additional \$0.1–\$1.20/lb (depending on manufacturing scale) more than baseline resins. However, they reduce life cycle cost by more than \$1.20/lb, making them economically feasible.</p>				
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## **Executive Summary**

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### **Background**

Composite materials are used in the U.S. Department of Defense (DOD) because of their low weight and excellent properties, enabling the production of lighter-weight and stronger vehicles, ships, and structures. Programs have been initiated to replace metallic components of high-mobility multipurpose wheeled vehicles (HMMWVs) and other Army vehicles and naval ships with composite parts. However, fabrication of composite materials can produce large amounts of volatile organic compound (VOC) and hazardous air pollutant (HAP) emissions.

The U.S. Army Research Laboratory (ARL)/Drexel have developed low-HAP fatty acid vinyl ester (FAVE) resin systems that would allow DOD facilities to continue manufacturing vinyl ester (VE) resins using current practices and facilities while reducing pollution and health risks. These resins reduce HAP content in composite resins by using fatty acid monomers as styrene replacements and bimodal molecular weight distributions of vinyl ester monomers to maintain high performance while using low-styrene/HAP contents.

### **Objectives of the Demonstration**

The objectives of this program were threefold:

1. Demonstrate/validate the processing and performance of low-VOC/HAP resins developed by ARL/Drexel as a viable alternative to current VE and unsaturated polyester (UPE) systems used in the DOD.
2. Quantify the impact of these resins on facility-wide HAP emissions at selected facilities and DOD contract manufacturing sites, and demonstrate compliance with proposed National Emissions Standard for Hazardous Air Pollutants (NESHAP) standards and existing composites NESHAP standards through monitoring and record keeping.
3. Demonstrate cost-savings potential for transitioning to low-VOC/HAP VE and UPE resins relative to using standard commercial resins or implementing facility modifications.

### **Demonstration Results**

The FAVE resin technology was demonstrated/validated on a variety of weapons platforms. For the Army, composite materials for tactical vehicles (M35A3 hood, M939 hood, and HMMWV transmission box) were demonstrated. For the Marines, low-VOC/HAP FAVE was used to demonstrate a ballistic HMMWV hardtop that currently uses high-VOC/HAP VE resins. For the Air Force, these low-HAP resins were used to replace current resins used in a composite dorsal cover for the T-38, F-22 canopy cover, and splash molds. This resin was also used to replace VE

resins currently used for the composite rudder on mine countermeasure (MCM) ships and current and future classes of destroyers (DDG and DDX, respectively).

FAVE resin formulations were developed by ARL/Drexel by blending methacrylated fatty acid (MFA) with various commercial VE resins to produce formulations with properties similar to current resins. A variety of resin formulations were prepared in this manner and then transitioned to Applied Poleramics, Inc. (API), for production. API of Benicia, CA, was successful in manufacturing the MFA monomers used to partly replace styrene in FAVE. Furthermore, API was successful in manufacturing the FAVE resins. Although initial batches of the MFA and FAVE did not pass all Joint Test Protocol (JTP) testing, after some slight modifications to the manufacture or formulation, all batches subsequently passed all JTP testing.

ARL/Drexel validated composite panels prepared using the resins developed by API and the fibers used in each of the demonstrations. ARL/Drexel did standard mechanical testing as well as accelerated aging and fatigue of these materials. The results indicated that the FAVE performed very similarly to commercial resins but had improved fatigue and weathering properties. Furthermore, each partner group completed panel testing and flow/infusion testing to find that the FAVE resins passed all requirements.

A FAVE resin formulation was demonstrated/validated on three Air Force platforms. The demonstration parts were then validated and showed that the FAVE resin performed similarly to the commercial VE resins used in these applications. A FAVE resin formulation was successfully demonstrated/validated on the MCM rudder. Structural Composites, Inc., successfully manufactured two FAVE rudders. One of the rudders was cross sectioned and was found to have excellent fiber wet-out and few defects. The second rudder will be kept on hand to potentially validate its use on the MCM once approval is granted by the Navy. Ballistic testing of panels for the Marines HMMWV hardtop application showed superior performance of the FAVE resins.

A FAVE resin was demonstrated/validated for composite Army applications (M35A3 hood, M939 hood, and HMMWV transmission container). Composite demonstration parts were prepared in the laboratory to prove that the FAVE resin could successfully be used for this application. Composites were then prepared at Sioux Manufacturing Corp. (SMC) to validate the resin processing and prepare parts for validation testing. SMC was satisfied with the processability of the resins and successfully produced the composite parts alongside parts using commercial resins. These manufactured parts were then validated on a test frame at the Center for Composite Materials. The results from the test-frame experiments showed identical performance of the FAVE composite vs. the commercial resins, and the FAVE composites passed all required specifications. The composite hoods were tested for form, fit, and function at the Red River Army Depot (RRAD) and passed all requirements. The composite containers were tested at the Aberdeen Test Center (ATC) for shock and vibration testing according to specifications for shipping containers. The results indicated that the FAVE passed all

requirements. RRAD validated the FAVE and commercial resin containers by shipping the containers around the depot for a period of 3 months. The results again showed very similar behavior for the FAVE and commercial resins. However, both the RRAD and ATC testing indicated some issues.

A life cycle analysis of the FAVE resins was performed by two independent groups. The results showed in all cases that the FAVE resins were more expensive per pound of resin than the commercial resins. However, when considering costs associated with emissions capture, FAVE resins become more competitive. In general, production of composites tended to favor the use of FAVE resins, such as in the Army demonstrations. However, smaller-scale uses, such as the Navy and Air Force demonstrations, favored the commercial resins.

### **Implementation Issues**

The FAVE resins are qualified for the Army hoods, HMMWV transmission container, canopy cover, and splash molds. The MCM rudder must undergo field testing, but approvals for that will take 2–3 years. The HMMWV hardtop no longer has a market, thus further implementation is pointless. The production of FAVE resins is in transition as Dixie Chemicals, Inc., has recently licensed the MFA and FAVE technology, precluding API from manufacturing it.

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# 1. Introduction

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## 1.1 Background

Composite materials are used in the Department of Defense (DOD) because of their low weight and excellent properties, enabling the production of lighter-weight and stronger vehicles, ships, and structures. Programs have been initiated to replace metallic components of the high-mobility multiwheeled vehicle (HMMWV) and other Army vehicles and naval ships with composite parts; future classes of vehicles and ships will use significantly higher amounts of composite materials, making these vehicles lighter, faster, and more maneuverable (figure 1). However, aspects of these technologies have an adverse effect on the environment. Fabrication of composite materials can produce large amounts of volatile organic compound (VOC) and hazardous air pollutant (HAP) emissions. Sources of pollution from these materials include the disposal of hazardous polymer ingredients, solvents used for viscosity reduction, gases evolved during and after processing, and the disposal of contaminated scrap materials (1).

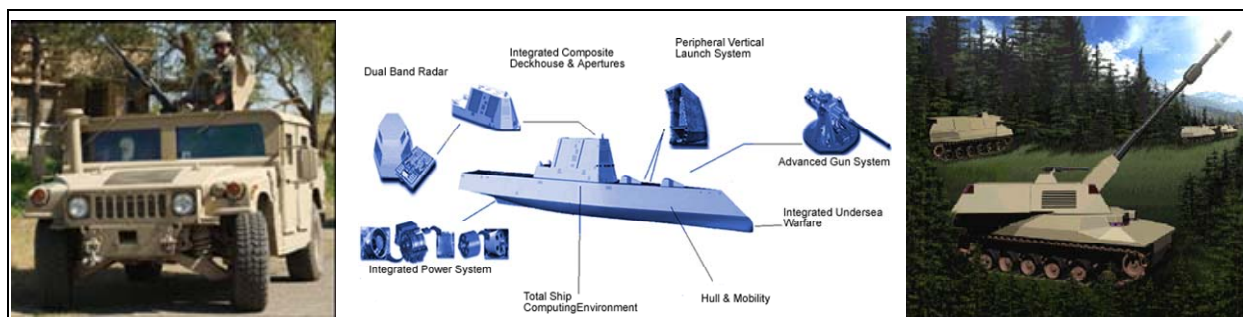


Figure 1. Current and future uses of composite materials in the military include the HMMWV, Navy DDX, and Crusader.

Reactive diluents in vinyl ester (VE) and unsaturated polyester (UPE) resins, such as styrene and methyl methacrylate, are used to reduce the resin viscosity to enable liquid molding. However, these diluents are VOCs and HAPs that are regulated by the Environmental Protection Agency (EPA) (2). Emissions controls can be implemented, but the cost of this is often prohibitive (3). Typical commercial resins contain 40–60 weight-percent (wt.%) styrene. There are some low-HAP varieties that contain as little as 33 wt.% styrene, such as Derakane 441-400. However, the viscosity and fracture properties of such resins are poor. Various solutions have been proposed over the years, but most suffer from a number of drawbacks that have prevented their implementation (4).

The U.S. Army Research Laboratory (ARL)/Drexel have developed low-HAP VE and unsaturated polyester resin systems that would allow DOD facilities to continue manufacturing VE resins using current practices and facilities while reducing pollution and health risks. These resins reduce HAP content in composite resins by using fatty acid monomers as styrene

replacements and bimodal molecular weight distributions of VE monomers to maintain high performance while using low-styrene/HAP contents.

## **1.2 Objective of the Demonstration**

The objectives of this program were to demonstrate/validate the processing, performance, and cost savings of low-VOC/HAP resins developed by ARL/Drexel as a viable alternative to current VE and UPE systems for HMMWW ballistic hardtops, HMMWV transmission containers, M35A3 and M939 truck hoods, mine countermeasure (MCM) composite rudders, splash molds for wing repair, and F-22 canopy covers.

This project sought to expand the use of the low-VOC/HAP materials developed in the Strategic Environmental Research and Development Program PP-1271 into the Army, Marines, Air Force, and Navy (figure 2). For the Army, composite materials for tactical vehicles (M35A3 hood, HMMWV hood, or HMMWV transmission box) were demonstrated. For the Marines, low-VOC/HAP VEs were used to manufacture and demonstrate a ballistic HMMWV hardtop that currently uses high-VOC/HAP VE resins. For the Air Force, these low-HAP resins were used to replace current resins used in a composite dorsal cover for the T-38. This resin was also used to replace VE resins currently used for the composite rudder on MCM ships and current and future class of destroyers (DDG and DDX, respectively). However, the DOD does very little composite manufacture. Most composite parts are provided to the DOD through contracting industry. On the other hand, the DOD does some composite repair at facilities, such as the Red River Army Depot (RRAD). Therefore, this proposed Environmental Security Technology Certification Program (ESTCP) work not only validated the use of low-VOC/HAP resins at DOD-contracted industry for military vehicle body parts, but also validated their use at DOD repair facilities.

ARL/Drexel focused on optimizing the resin for a particular application. Applied Poleramics, Inc. (API), produced the low-VOC/HAP resins to be used throughout this work. The University of Delaware Center for Composite Materials (CCM) and ARL designed, fabricated, and tested composite panels for Army, Marine, and Navy applications. The U.S. Air Force Research Laboratory at Hill Air Force Base fabricated and tested these composites for Air Force applications. RRAD and ARL/Aberdeen Proving Ground (APG) performed a field trial of these low-VOC/HAP composites. Structural Composites, Inc. (SCI), performed mechanical testing of the composite rudder in conjunction with the Naval Surface Warfare Center Carderock Division (NSWCCD) and the CCM. SCI and Sioux Manufacturing Corp. (SMC) and TPI Composites produced the low VOC/HAP composite parts on a larger scale for the DOD.

These demonstrations will show whether ARL/Drexel low HAP resins can be used to replace commercial VE and unsaturated polyester resins. As such, composite performance must be maintained, life-cycle cost must be maintained or decreased, and HAP content must be significantly lowered below NESHAP regulations relative to commercial resins.





Figure 2. This program demonstrated/validated low-HAP VE resin composites for (a) HMMWV ballistic hardtop, (b) HMMWV transmission container, and one to two types of composite replacement hoods including (c) M939, (d) M35A3, or (e) HMMWV, and (f) MCM rudder, (g) T-38 dorsal cover, and (h) F-22 canopy cover.

### **1.3 Regulatory Drivers**

Reactive diluents in VE and UPE resins, such as styrene and methyl methacrylate, are used to reduce the resin viscosity to enable liquid molding. However, these diluents are VOCs and HAPs. HAPs were defined by the 1990 Clean Air Act Amendments (Section 112) (5) as chemicals that must have emissions limits. These chemicals have adverse health effects, including headache, fatigue, depression, irritation, and cancer, and are damaging to the environment. VOCs evaporate at substantial rates at room temperature and could potentially produce smog-promoting ozone as well as long-term and acute health effects. VOC/HAPs are emitted during all phases of composite fabrication. By means of the Clean Air Act (5), the EPA has enacted the Reinforced Plastic Composites National Emissions Standards for Hazardous Air Pollutants (NESHAP) to limit styrene emissions from composite manufacturing (2). This legislation could have a significant impact on the use of composite materials in military as well as commercial applications unless methods for mitigating VOC/HAP emissions during composite processing, curing, and fielding of the composite part are developed. Current high-performance resins typically contain ~40–50 wt.% HAP content. The new regulations require the HAP content to be effectively ~30 wt.%, resulting in emissions reduction of ~8000 ton/year. Although some commercial resins have as little as 30 wt.% HAP content, they suffer from poor material properties.

Through implementation of the Clean Air Act and Clean Water Act, the EPA has established regulations limiting the amount of VOCs, HAPs, and heavy metals that can be used in composite materials. Although there are commercial resin systems that meet the current NESHAP requirements for individual DOD facilities, these resins have poor performance and processability. Therefore, DOD facilities would need to implement add-on control devices to capture volatile emissions from composite processing in order to use the high-performance commercial resins. Considering the number of current and future DOD sites using composite resins, the cost of implementing these add-on facilities would be prohibitive (3). The alternatives are to use more expensive epoxy resins (approximately three times more expensive) or to reduce the use of composites in the DOD, making it difficult to realize the initiative to make a lighter, faster, and more maneuverable military.

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## **2. Demonstration Technology**

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### **2.1 Low-HAP Resin Technology Description**

Typical commercial VE and unsaturated polyester resins contain 40–60 wt.% styrene or other reactive diluent. These resins will not be NESHAP compliant. Commercial industry has developed low-HAP resins, such as Derakane 441-400 and Reichhold Hydrex 100-LV, which have a low HAP content and are NESHAP compliant for most composite fabrication applications. However, the fracture toughness and viscosities of these resins are poor and

unacceptable for most military use. ARL/Drexel has developed two solutions for making NESHAP-compliant resins with excellent resin and polymer performance: fatty acid vinyl ester (FAVE)/unsaturated polyester (UPE) and bimodal vinyl ester (BMVE) (figure 3). The FAVE/UPE resin uses fatty acid monomers (6) as a reactive diluent to replace all but ~20 wt.% of the styrene HAP in the VE or UPE resin (4). The BMVE resin uses a mixture of low and high molecular weight VE monomers (i.e., bimodal) to reduce resin viscosity and improve fracture performance while using only 28–38 wt.% styrene (7). The patented solutions (6, 8) are depicted in figure 3 and involve replacing conventional reactive diluents with plant oil–derived monomers and altering the molecular structure of the cross-linking agent to reduce the styrene content in these resins.

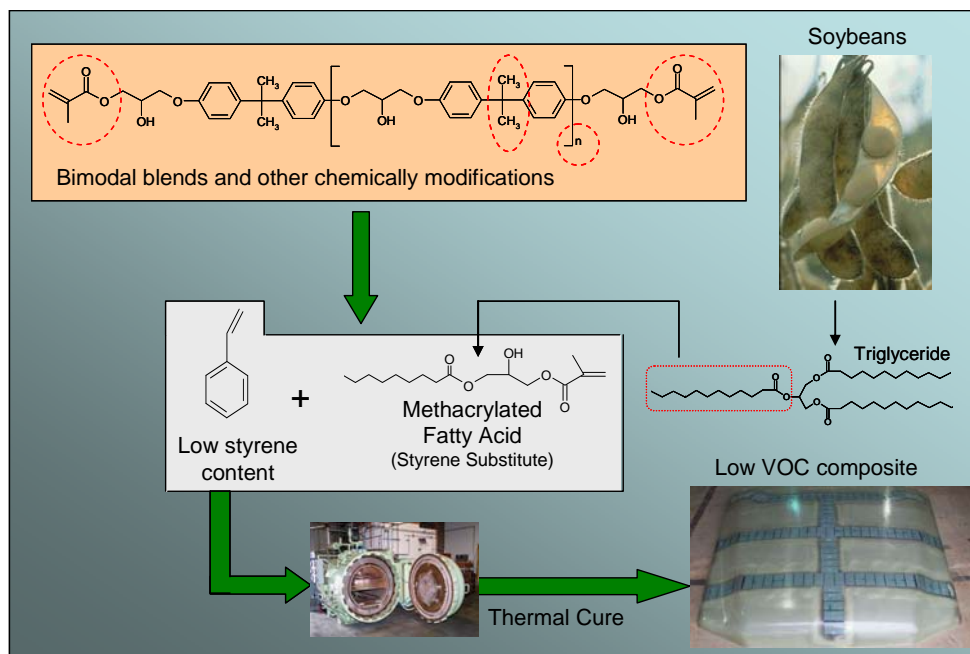


Figure 3. Methods to reduce VOC/HAP emissions in thermosetting resins.

Methacrylated fatty acid (MFA) monomers are produced through a simple addition reaction of the carboxylic acid of fatty acids with the epoxide group of glycidyl methacrylate to form a single product within a few hours at temperatures ranging from room temperature to 80 °C (4, 6). Each MFA contains one terminal polymerizable unsaturation site per molecule. In this way, the fatty acid monomers act as chain extenders, analogous to styrene, in VE resins. The resulting monomers have fairly high molecular weight and are nonvolatile, making them excellent alternatives to styrene in liquid molding resins. Furthermore, these monomers promote global sustainability because they are made using a renewable resource. Numerous fatty acids have been used to make MFA monomers. The molecular structures of the fatty acids used do have an effect on the polymer and resin properties. The resin viscosity decreases and polymer properties increase as fatty acid chain length decrease (4), but cost is also a factor. Methacrylated lauric acid monomers represent a balance of these factors, as they have good resin and polymer

properties, and low cost. Because of the low cost of fatty acids and the simple modifications to produce fatty acid monomers, these monomers are inexpensive, with an estimated cost only slightly above that of styrene. Although plant oils have been used to make polymers for years, the use of fatty acid monomers as reactive diluents is a novel concept (6).

Ideally, all of the styrene in VE and unsaturated polyester resins could be replaced with fatty acid-based monomers; however, the resulting resin and polymer properties are poor relative to commercial resins. Therefore, rather than completely replacing styrene with fatty acid monomers, styrene was partially replaced with the fatty acid monomers. Styrene contents ranging from 10 to 20 wt.% (55%–78% reduction in VOC/HAP content relative to commercial resins) were used, resulting in good resin and polymer properties. The resin viscosities were far below the threshold for liquid molding processes (1000 cP) and have been successfully used to produce defect-free composite parts at high production rates (9, 10). The glass transition temperature was similar to commercial resins ( $>120\text{ }^{\circ}\text{C}$ ), and the toughness was twice that of commercial resins. On the other hand, the stiffness and strength were a bit lower than that of commercial resins while still having moduli over 3 GPa and strength over 100 MPa. Composite properties were very similar to similar composites made using commercial resins. In addition, part shrinkage was reduced by more than 50% relative to commercial resins, helping to maintain dimensional stability. Thermo gravimetric analysis results showed that the fatty acid monomers are not volatile, and resins formulated with these monomers produce only styrene emissions. Therefore, these MFA monomers do indeed reduce the VOC/HAP content in composite resins.

## **2.2 Advantages and Limitations of the Technology**

The main advantage of the ARL/Drexel low-HAP resins is their low HAP content while maintaining low resin viscosity and high fracture properties. For the FAVE resin, low part shrinkage and partly renewable chemical makeup is also an advantage. The FAVE resins have a longer shelf life relative to styrenated resins and low-HAP acrylate-based resins.

There are several factors that can impact the startup and recurring cost of the ARL/Drexel low-HAP resins. The main cost driver is that the FAVE resins are currently only produced on a small scale relative to that of commercial composite resins. Larger-scale machinery, chemical reactants, etc., would lower the cost. The licensing of this technology by Dixie Chemicals could easily occur if a large resin supplier licensed and produced this technology. The cost of the glycidyl methacrylate, one of the reactants used to produce the fatty acid monomers, is currently high because of high petroleum costs and has a strong effect on resin cost. The fatty acid type also affects the cost. Shorter fatty acids, such as octanoic acid, are more expensive than longer acids, such as lauric acid. Novolac resins are more expensive than bisphenol A-based VE resins. Therefore, the required use of either of these higher-performance resins affects the cost. Although the resin cost per pound is more for the low-HAP resins, it is important to assess the life cycle costs. An advantage of the FAVE resins is that they would not require an investment of capital equipment to capture HAP emissions.

FAVE-O resins and those using Novolac VEs improve the thermal properties, but also increase the cost. Therefore, it was important to assess the ability of these resins to meet moderate temperature requirements that these composite parts will be exposed to.

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### **3. Performance Objectives**

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There are numerous performance objectives for this project. The initial performance objective is to demonstrate the scale-up of the MFA monomers and low-HAP resins. The low-HAP resin was demonstrated/validated for applications in Army hood applications, HMMWV transmission container, Marines HMMWV hardtop, Air Force T-38 dorsal cover, F-22 canopy cover, and splash mold, and Navy composite rudder.

#### **3.1 Resin Quality Control**

It is possible that the MFA monomers are not completely reacted after the scaled-up process. Also, incorrect mix ratios of reactants or components can be used to create resins with incorrect formulations. As a result, quality control of these resins is necessary to validate the scale-up of these resins and to assure uniformity of the resins from batch to batch for other DOD composite demonstrations.

The quality control of resin scale-up was tested using a set of five tests as described in the Joint Test Protocol (JTP). ASTM D 1980-87 (11) was used to access the acid number of MFA monomers (table 1) and resins (table 2). This test determined if there was too much free acid remaining in the system and indicated whether incomplete conversion of the reactants into the MFA and VE monomers occurred. Fourier transform infrared spectroscopy (FTIR) testing was used to determine the presence of unreacted epoxy groups. Unreacted epoxy groups indicated incomplete conversion of the reactants in the MFA and VE monomers. Nuclear magnetic resonance (NMR) spectroscopy will be used to determine various chemical aspects of the resins. First, the quantity of unreacted epoxy groups was measured. The ratio of methacrylate groups to VE or MFA monomers was quantified. Also, the molar ratio of VE/MFA/styrene in FAVE was quantified. Lastly, a rheometer was used to measure this viscosity of the MFA monomers and resins at 25 °C. Too high of a viscosity indicated side reactions occurred that degraded the resin properties and processability. Size Exclusion Chromatography (SEC) was used to determine the content of high-molecular weight species in the MFA monomers and FAVE resins.

Table 1. Common performance and testing requirements for the FAVE monomer.

<b>Performance Requirement</b>	<b>Data Requirement</b>	<b>Success Criteria</b>	<b>Results</b>
Acid number	ASTM D 1980-87 (11)	Acid number <20	Acid number <20
Viscosity at 25 °C	Viscometer, rheometer	Viscosity <80 cP at 25 °C (MLau) Viscosity <70 cP at 25 °C (MOct)	Viscosity <80 cP at 25 °C (MLau) Viscosity <70 cP at 25 °C (MOct)
Unreacted epoxy	FTIR, NMR	No epoxy present	None detected
Correct reactant ratios	NMR	Methacrylate-to-FA ratio of 1:1 (+0.05, -0.1)	Ratio ranged from 1.05:1 to 1:0.9

Table 2. Common performance and testing requirements for the FAVE resin.

<b>Performance Requirement</b>	<b>Data Requirement</b>	<b>Success Criteria</b>	<b>Results</b>
Acid number	ASTM D 1980-87 (11)	Acid number <5	Acid number <5
Viscosity at 25 °C	Viscometer, rheometer	Viscosity <1000 cP at 25 °C	Viscosity <1000 cP
Unreacted epoxy	FTIR, NMR	No epoxy present	None detected
Correct reactant ratios	NMR	Methacrylate-to-FA ratio of 1:1 (+0.05, -0.1)	Ratio ranged from 1.05:1 to 1:0.9
Correct VE MW	NMR, SEC	VE MW <700 g/mol (Bisphenol A) VE MW <900 g/mol (Novolac)	Bisphenol VE MW <700 g/mol
Correct component ratios	NMR, SEC	VE-to-MFA-to-styrene ratio should be $\pm 5\%$ based on desired formulation	VE-to-MFA-to-styrene ratios were within 5% of specified
Gel time	ASTM D 2471-99 (12)	Variable gel time from 10 min to 5 h	Gel times ranged from 5 min to 5 h
Production scale ability of low-HAP resins	Production scale ability of low-HAP resins	Pass individual tests described in JTP	Simple production Production is scalable Passed JTP tests

The following engineering requirements are for the JTP for monomer and resin validation:

- Monomer acid number: high acid number indicates incomplete reaction.
- Resin acid number: high acid number indicates incomplete reaction.
- Monomer viscosity: high resin viscosity indicates side reactions occurred that degrade the monomer and resin properties.
- Resin viscosity: high resin viscosity hurts the ability to process the resin and form a good composite.

- No unreacted epoxy: unreacted epoxy indicates the MFA or BMVE reaction was not run to completion. This degrades resin performance and increases toxicity of the MFA resin.
- Correct reactant ratios: a methacrylate-to-fatty-acid ratio of 1:1 is desired for complete reaction and optimum resin properties.
- Correct VE molecular weight: low molecular weight VEs are desired to reduce resin viscosity.
- Correct VE/MFA/styrene ratio: resins formulations have been established with optimum properties. Changing the formulation affects the properties.
- Gel time: ability to vary the gel time from as short as 15 min to as long as 4 h.

### 3.2 Demonstration/Validation of Composites Using FAVE Resins

Objectives for any of the HMMWV hood, M35A3 hood, and M939 hood are to meet or exceed all relevant performance parameters of the material system without an increase in weight (table 3). These parameters included targets for coupon-level thermal and mechanical performance static loading, cyclic loading, impact resistance, and processability (viscosity and gel time), and the hood must be able to fit on an appropriate truck. Because both the M35A3 and M939 hoods were validated, the HMMWV hood was not demonstrated in this work. However, the validation results for the FAVE resins show that FAVE should be valid for HMMWV hood applications.

Table 3. Performance objectives for Army hoods with appropriate fabric reinforcement for application.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance
Quantitative	Dry T <sub>g</sub> through DMA test	>250 °F	289 °F
Quantitative	Wet T <sub>g</sub> through DMA test	>225 °F	271°F
Quantitative	Flexural strength at RT (ASTM D 790) (13)	≥55 ksi	62 ksi
Quantitative	Flexural strength at 250 °F (ASTM D 790) (13)	≥30 ksi	37 ksi
Quantitative	Flexural modulus at RT (ASTM D 790) (13)	≥3.7 Msi	3.8 Msi
Quantitative	Flexural modulus at 250 °F (ASTM D 790) (13)	≥3.0 Msi	3.1 Msi
Quantitative	SBS strength at RT (ASTM D 2344) (14)	≥4.5 ksi	4.6 ksi
Quantitative	SBS strength at 250 °F (ASTM D 2344) (14)	≥3.0 ksi	3.3 ksi

Table 3. Performance objectives for Army hoods with appropriate fabric reinforcement for application (continued).

<b>Type of Performance Objective</b>	<b>Primary Performance Criteria</b>	<b>Expected Performance (Metric)</b>	<b>Actual Performance</b>
Quantitative	Top center loading - HMMWV hood - M35A3 hood - M939 hood	≤0.5 in deflection ≤0.5 in deflection ≤0.5 in deflection	Not performed 0.1 in 0.11 in
Qualitative	Top center loading - M939 hood - M35A3 hood - M939 hood	No damage No damage No damage	Not performed No damage No damage
Quantitative	Top front loading - HMMWV hood - M35A3 hood - M939 hood	≤0.5 in deflection ≤0.5 in deflection ≤0.5 in deflection	Not performed 0.04 in 0.03 in
Qualitative	Top front loading - M939 hood - M35A3 hood - M939 hood	No damage No damage No damage	Not performed No damage No damage
Quantitative	Driver/passenger flexural static lifts - HMMWV hood - M35A3 hood - M939 hood	>50 lb for 0.375 in >50 lb for 0.375 in >50 lb for 0.375 in	Not performed 0.015 in at 50 lb 0.2 in at 50 lb
Qualitative	Driver/passenger flexural static lifts - HMMWV hood - M35A3 hood - M939 hood	≤ cosmetic damage ≤ cosmetic damage ≤ cosmetic damage	Not performed Cosmetic damage Cosmetic damage
Qualitative	Impact resistance - HMMWV hood - M35A3 hood - M939 hood	≤ cosmetic damage ≤ cosmetic damage ≤ cosmetic damage	Not performed Cosmetic damage Cosmetic damage
Qualitative	Cyclic hood testing – top center loading - HMMWV hood - M939 hood - M35A3 hood	No damage No damage No damage	Not performed No damage No damage
Qualitative	Cyclic hood testing – passenger and driver corners - HMMWV hood - M939 hood - M35A3 hood	No damage No damage No damage	Not performed No damage No damage
Quantitative	Top center loading after cyclic testing - HMMWV hood - M35A3 hood - M939 hood	≤0.5 in deflection ≤0.5 in deflection ≤0.5 in deflection	Not performed 0.1 in 0.11 in
Qualitative	Top center loading after cyclic testing - M939 hood - M35A3 hood - M939 hood	No damage No damage No damage	Not performed No damage No damage



Table 3. Performance objectives for Army hoods with appropriate fabric reinforcement for application (continued).

<b>Type of Performance Objective</b>	<b>Primary Performance Criteria</b>	<b>Expected Performance (Metric)</b>	<b>Actual Performance</b>
Quantitative	Top front loading after cyclic testing - HMMWV hood - M35A3 hood - M939 hood	≤0.5 in deflection ≤0.5 in deflection ≤0.5 in deflection	Not performed 0.04 in 0.03 in
Qualitative	Top front loading after cyclic testing - M939 hood - M35A3 hood - M939 hood	No damage No damage No damage	Not performed No damage No damage
Quantitative	Driver/passenger flexural static lifts after cyclic testing - HMMWV hood - M35A3 hood - M939 hood	>50 lb for 0.375 in >50 lb for 0.375 in >50 lb for 0.375 in	Not performed 0.015 in at 50 lb 0.2 in at 50 lb
Qualitative	Driver/passenger flexural static lifts after cyclic testing - HMMWV hood - M35A3 hood - M939 hood	≤ cosmetic damage ≤ cosmetic damage ≤ cosmetic damage	Not performed Cosmetic damage Cosmetic damage
Qualitative	Resin fills part in allotted time - HMMWV hood - M939 hood - M35A3 hood	Fabricator approval Fabricator approval Fabricator approval	Not performed Resin filled part Resin filled part
Qualitative	Resin gels in correct amount of time for hood - HMMWV hood - M939 hood - M35A3 hood	Fabricator approval Fabricator approval Fabricator approval	Not performed Appropriate gel time Appropriate gel time
Qualitative	Resin fully wets fibers for hood - HMMWV hood - M939 hood - M35A3 hood	Fabricator approval Fabricator approval Fabricator approval	Not performed Resin fully wet fibers Resin fully wet fibers
Qualitative	Field test hood - HMMWV hood - M939 hood - M35A3 hood	Depot approval Depot approval Depot approval	Not performed Good performance Good performance

The HMMWV transmission container must be able to withstand the damage associated with shipping (table 4). Thus fully loaded containers were tested under field trials and using lab validation scenarios that would be experienced in fielding environments. These included dropping the container from a height, stacking the containers, dropping items onto the container, and tipping over the container. In addition, some basic properties had to be achieved in composite laminate coupons.

Table 4. Performance objectives for HMMWV transmission container with appropriate fabric reinforcement for application.

<b>Type of Performance Objective</b>	<b>Primary Performance Criteria</b>	<b>Expected Performance (Metric)</b>	<b>Actual Performance</b>
Quantitative	Dry T <sub>g</sub> through DMA test	>200 °F	257 °F
Quantitative	Wet T <sub>g</sub> through DMA test	>180 °F	239 °F
Quantitative	Flexural strength at RT (ASTM D 790) (13)	≥55 ksi	69 ksi
Quantitative	Flexural modulus at RT (ASTM D 790) (13)	≥3.7 Msi	3.8 Msi
Quantitative	SBS strength at RT (ASTM D 2344) (14)	≥4.5 ksi	5.0 ksi
Qualitative	Resin fills part in allotted time	Fabricator comments and approval.	Resin filled part in allotted time. Resin performed well according to fabricators.
Qualitative	Resin gels in correct amount of time	Fabricator comments and approval.	Resin gel time was controllable from short to long times. Resin performed well according to fabricators.
Qualitative	Resin fully wet fibers	Fabricator comments and approval.	Resin fully wet fibers. Resin performed well according to fabricators.
Qualitative	Field test of container	User comments.	Good performance.
Qualitative	Edgewise drop before and after fielding	No permanent deformation; separation of reinforcements or cracks observed.	No permanent deformation; separation of reinforcements or cracks observed.
Qualitative	Cornerwise drop before and after fielding	No permanent deformation; separation of reinforcements or cracks observed.	No permanent deformation, separation of reinforcements or cracks observed.
Qualitative	Tip over before and after fielding	No permanent deformation; separation of reinforcements or cracks observed.	No permanent deformation; separation of reinforcements or cracks observed.
Qualitative	Trans. container external pressure	≤0.22 in deformation. ≤0.09% in plane strain.	Passed.
Qualitative	Impact before and after fielding	No permanent deformation; separation of reinforcements or cracks observed in the container composite structure.	No permanent deformation; separation of reinforcements or cracks observed in the container composite structure.
Qualitative	Flatwise drop before and after fielding	No permanent deformation; separation of reinforcements or cracks observed.	No permanent deformation; separation of reinforcements or cracks observed.

Table 4. Performance objectives for HMMWV transmission container with appropriate fabric reinforcement for application (continued).

<b>Type of Performance Objective</b>	<b>Primary Performance Criteria</b>	<b>Expected Performance (Metric)</b>	<b>Actual Performance</b>
Qualitative	Stacking before and after fielding	No slippage was observed, and the fork truck was able to perform this task.	No slippage was observed, and the fork truck was able to perform this task.
Qualitative	Concentrated load resistance before and after fielding	No permanent deformation; separation of reinforcements or cracks observed.	No permanent deformation; separation of reinforcements or cracks observed.
Qualitative	Impact resistance before and after fielding	Insignificant/minor cracking of the resin. No permanent deformation.	Insignificant/minor cracking of the resin. No permanent deformation.
Qualitative	Field test before and after fielding	Depot inspector comments.	Field tests showed good performance of resin and similar to that of baseline resin.

Objectives for the Amtech HMMWV ballistic hardtop were to meet or exceed all relevant performance parameters of the material system without an increase in weight (table 5). Note that the 3000-mi durability test and the ballistics performance of the sandwich coupon were not performed. This is because testing done on other platforms and coupons validated the part without need for these tests.

Table 5. Performance objectives for Marines HMMWV hardtop.

<b>Type of Performance Objective</b>	<b>Primary Performance Criteria</b>	<b>Expected Performance (Metric)</b>	<b>Actual Performance</b>
Quantitative	Dry T <sub>g</sub> through DMA test	>250 °F	257 °F
Quantitative	Wet T <sub>g</sub> through DMA test	>200 °F	239 °F
Quantitative	Four-point bend static sandwich testing (ASTM D 6272-98) (15)	≥9000 lb	12,000 lb
Quantitative	Four-point bend fatigue sandwich testing (ASTM D 6272-98) (15) at 5000 lb, R = 0.1 at 1 Hz	≥500,000 cycles	Test stopped at 500,100 cycles
Quantitative	SBS static sandwich testing (ASTM D 2344) (14)	≥2 ksi	3 ksi
Quantitative	SBS fatigue sandwich testing (ASTM D 2344) (14) at 1.1 ksi at R = 0.1 at 1 Hz	≥500,000 cycles	Test stopped at 500,100 cycles

Table 5. Performance objectives for Marines HMMWV hardtop (continued).

<b>Type of Performance Objective</b>	<b>Primary Performance Criteria</b>	<b>Expected Performance (Metric)</b>	<b>Actual Performance</b>
Qualitative	Ballistic coupon testing	V50 Level IIIa at ~4 psf V50 Level III at ~12 psf V50 Level III in sandwich configuration with HJ1 phenolic core – total AD ~10.5 psf	Passed Passed Not tested
Qualitative	Hardtop 3000-mi off-road test	Depot inspector comments	Testing not performed.
Qualitative	Resin fills part in allotted time	Fabricator comments and approval	Resin filled part in allotted time. Resin performed well according to fabricators.
Qualitative	Resin gels in correct amount of time	Fabricator comments and approval	Resin gel time was controllable from short to long times. Resin performed well according to fabricators.
Qualitative	Resin fully wets fibers	Fabricator comments and approval	Resin fully wet fibers. Resin performed well according to fabricators.
Qualitative	Fatigue testing	Similar or better than incumbent resin	Superior performance relative to incumbent.

The APG ballistics range was used to determine V50 numbers for the composites used for Army and especially Marine applications. The samples must meet V50 level IIIa at ~4 psf, V50 level III at ~12 psf, and V50 level III in sandwich configuration with HJ1 phenolic core, total areal density ~10.5 psf. Because the durability testing was not done, fatigue testing results were added to the matrix to ensure adequate fatigue performance of the resin. In addition, some basic properties had to be achieved in composite laminate coupons.

The Air Force had to have processable resins with moderate property requirements for their applications (table 6). The resins needed to be able to form rigid parts that maintain their performance in ambient conditions.

Table 6. Performance objectives for Air Force T-38 dorsal cover, splash molds, and F-22 canopy cover.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance
Qualitative	Resin fills part in allotted time	Fabricator comments and approval	Resin filled part in allotted time. Resin performed well according to fabricators.
Qualitative	Resin gels in correct amount of time	Fabricator comments and approval	Resin gel time was controllable from short to long times. Resin performed well according to fabricators.
Qualitative	Resin fully wets fibers	Fabricator comments and approval	Resin fully wet fibers. ACO approved resin.
Qualitative	Flight test	Depot inspector comments and approval	Flight test did not occur.
Qualitative	Flight test	Rigid structure that maintains shape at fielding temperatures	Passed.

Resins used for Navy rudders must have properties to enable them to work at high shears where potentially high local temperatures are achieved (table 7). The composites must also perform well in wet environments. The resins must be processable to form a large composite part.

Table 7. Performance objectives for Navy composite rudder.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance
Quantitative	Wet T <sub>g</sub> through DMA test	>100 °C	>110°C
Quantitative	Water absorption	<5 wt. %	<0.4 wt. %
Quantitative	SBS strength at RT (ASTM D 2344) (14)	≥5.3 ksi	7.2 ksi
Quantitative	SBS strength at RT – wet (ASTM D 2344) (14)	≥5.3 ksi	6.2 ksi
Quantitative	Tensile modulus at RT (ASTM D 638) (16) - 0° - 90°	≥2.7 Msi ≥1.9 Msi	4.6 Msi 3.2 Msi
Quantitative	Tensile strength at RT (ASTM D 638) (16) - 0° - 90°	≥52 ksi ≥37 ksi	89 ksi 55 ksi

Table 7. Performance objectives for Navy composite rudder (continued).

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance
Quantitative	Tensile modulus at RT – wet (ASTM D 638) (16)	$\geq 2.6$ Msi	4.8 Msi
Quantitative	Tensile strength at RT – wet (ASTM D 638) (16)	$\geq 40$ ksi	85 ksi
Quantitative	Compressive modulus at RT (ASTM D 695) (17) - 0° - 90°	$\geq 2.7$ Msi $\geq 2.3$ Msi	4.5 Msi 3.7 Msi
Quantitative	Compressive strength at RT (ASTM D 695) (17) - 0° - 90°	$\geq 42$ ksi $\geq 38$ ksi	83 ksi 44 ksi
Quantitative	Compressive modulus at RT – wet (ASTM D 695) (17)	$\geq 2.0$ Msi	5.0 Msi
Quantitative	Compressive strength at RT – wet (ASTM D 695) (17)	$\geq 41$ ksi	45 ksi
Qualitative	Field test	Depot inspector comments	Part not yet fielded.
Qualitative	Resin fills part in allotted time	Fabricator comments and approval	Resin infused part in allotted time. Resin performed well according to fabricators.
Qualitative	Resin gels in correct amount of time	Fabricator comments and approval	Resin gel time was controllable from short to long times. Resin performed well according to fabricators.
Qualitative	Resin fully wets fibers	Fabricator comments and approval	Resin fully wet fibers. Resin performed well according to fabricators.

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## 4. Site/Platform Description

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### 4.1 Test Platforms/Facilities

Replacement hoods for the M35A3, M939, and HMMWV can be purchased. These hoods use composite materials and are typically manufactured with a VE (Hetron 980/35) with an additional 7 wt.% styrene added or Huntsman 8605 epoxy resin. The hood is designed to address corrosion and maintenance issues with the metal hoods used for M939 and M35A3 and to perform better than SMC hoods used for the HMMWV (18, 19). TPI Composites manufactures the HMMWV hood, while Sioux Manufacturing Corp. manufactures the M35A3 and M939 hoods.

RRAD is interested in developing a more robust method for shipping HMMWV transmissions, as current foam/wood containers often do not protect the transmissions from damage. The CCM has recently developed a VE-based shipping container to meet all of the packaging requirements to prevent transmission damage during shipment (20) and is developing the technical data package in conjunction with Sioux Manufacturing Corp. The containers use Derakane 8084 resin with 40 wt.% styrene, E-glass fiber, and foam to produce the composite. Past work shows excellent performance of these containers, but the resin used contains 40 wt.% HAPs.

Amtech has been producing similar hardtops for years but decided to develop a ballistic resistance hardtop to meet military operation needs. Traditional HMMWV hardtop designs did not protect well against small arms fire and needed to have add-on armor kits attached when used in dangerous situations. This increased the weight on the HMMWV, limiting its effectiveness. Thus, the Marines HMMWV helmet hardtop was developed by the CCM in conjunction with Amtech (20). The part exceeds all ballistic and structural requirements and has a relatively low cost (20). The part uses Derakane 8084 as the matrix resin, which is a toughened VE containing 40 wt.% styrene.

The Advance Composite Office (ACO) has a number of needs for VE resins for repair applications. The T-38 dorsal cover, F-22 canopy cover, and splash molds are examples that were demonstrated in this work. T-38 dorsal covers have had to be replaced because of delamination and other failures that have occurred as a recent upgrade that required cutting a hole in the dorsal cover (21). Because the T-38 is a legacy aircraft, there were no manufacturers of the part. The ACO developed a vacuum-assisted resin transfer molding (VARTM) dorsal cover replacement, but the resin, Hexion 781-2140, contains 47 wt.% styrene (21). The F-22 canopy cover is a need that was requested during the course of the ESTCP WP-0617 project. Protecting the sensitive coatings on the F-22 canopy is important during maintenance operations. The ACO has identified a solution through by developing a low-cost composite cover to protect the canopy. Splash molds are required to do repair on the underside of structures. The ACO does these repairs and helps others with the repairs frequently. Thus, they determined that a low-HAP resin such as the FAVE resins would be a good resin choice for this application, rather than using a standard VE.

NSWCCD developed the composite rudder as a solution to the cavitation problems that quickly cause severe damage to metallic rudders (22). The MCM composite rudder has been fielded on a single ship (MCM-9) as a test bed with excellent results so far. However, the resin used to manufacture this rudder was Corve 8100, which contains 50 wt.% styrene. Other composite rudders are also being considered, including a composite-twisted rudder for DDGs.

These applications currently use VE and E-glass reinforcement. The type of VE and E-glass reinforcement is different with each application. Thus, this work must assess the FAVE resin as a replacement with each of the E-glass fibers as test panels and as full part demonstration /validation.

## **4.2 Present Operations**

The low-HAP VE resins are intended to replace high-HAP VE resins used or considered for use on Army tactical vehicles, the Marines helmet hardtop, the T-38 dorsal cover, F-22 canopy cover, splash molds, and the MCM composite rudder currently used or being proposed for use. The SMC composites used for HMMWV hoods have poor performance and produce large amounts of styrene HAP during production. TPI Composites is producing the VARTM HMMWV hood (in an expanded capability vehicle HMMWV variant), which still contains a high-HAP resin content. The M35A3 and M939 composite hood is being produced by Sioux Manufacturing Corp., which currently uses a high-cost epoxy resin for these parts. The HMMWV transmission container is not currently in production from any company, but the current CCM design uses a high-HAP VE resin. The current T-38 dorsal cover is a hand lay-up unsaturated polyester resin glass-reinforced composite. The resin is a high-HAP unsaturated polyester, but this part is no longer produced. Therefore, current parts are repaired by machining and hand tooling. The VARTM T-38 dorsal cover recently designed by the ACO uses a high-HAP VE resin. This process has not yet been approved for Air Logistics Center use. A similar high-HAP resin would likely be used to produce F-22 canopy covers and splash molds. The MCM composite rudder was produced by Structural Composites, Inc., for a single MCM ship. The resin used is a high-HAP VE resin. It appears that composite rudders will become more prevalent in the next few years because of their excellent performance.

The ARL/Drexel low-HAP VE resin will simply be a drop-in replacement for conventional high-HAP VE resins used to make the parts previously listed using VARTM infusion methods. The demonstration will only slightly modify existing designs for these composite parts.

## **4.3 Site-Related Permits and Regulations**

These low-HAP composite resins are very similar to commercial composite resins. API, CCM, RRAD, Air Force, NSWCCD, Drexel, and ARL currently use commercial VE resins. As a result, most aspects of working with these resins will not be affected. All sites will need to add the FAVE and BMVE resins to their approved materials list before implementation, if applicable. However, composite resins are not typically listed on such lists. Furthermore, the use of these resins, as with all operational chemicals, will be governed by each site's pollution compliance permit and policy. The FAVE and BMVE resin still contain HAPs and therefore will be regulated under the Reinforced Plastics Composites NESHAP.

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## **5. Test Design**

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The experiment design is the same for the Army, Marines, Navy, and Air Force demonstrations. Figure 4 illustrates the experimental design. Resin was produced by API. Drexel and ARL performed quality control experiments to ensure the resins produced met the required



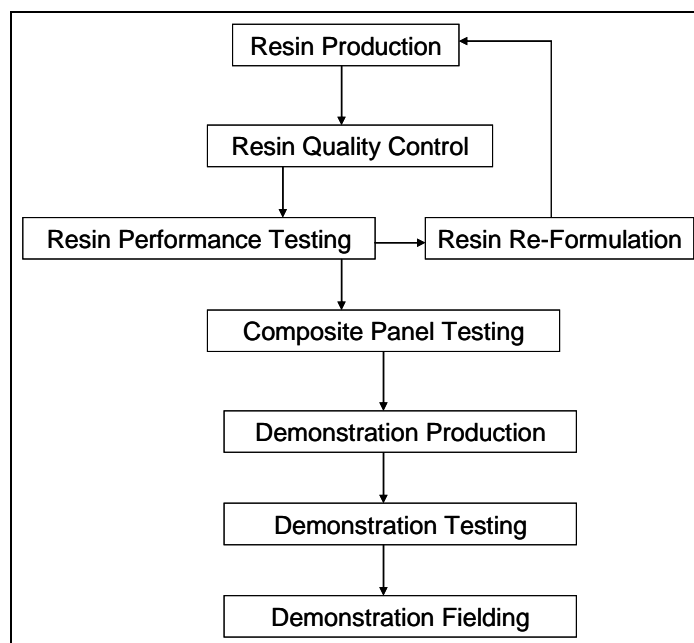


Figure 4. Demonstration/validation process design for FAVE resins used in DOD composite applications.

specifications. These tests involved ASTM acid number testing, rheometer viscosity testing, and NMR/FTIR chemical analysis. Furthermore, basic resin properties were measured using dynamic mechanical analysis (DMA) and Instron mechanical tests. If the properties were not high enough for a given application, resin variables were adjusted. These resin variables include using different VE types (novolac vs. bisphenol A), different fatty acid chain lengths, and different resin composition (VE/MFA /styrene ratios).

## 5.1 JTP Testing and Laboratory Experimentation

### 5.1.1 MFA and FAVE Resin Manufacture and Batch Testing

There are two manufacturing elements regarding FAVE resin manufacture: MFA manufacture and resin blending. Both elements were performed by API under the guidance of ARL/Drexel. The manufacture of MFA must be able to be simply performed by API at the scale of 1–55 gal. The reactants and additives must blend effectively, easily, and reproducibly. Resin component blending (MFA, commercial VE resins, and pure VE monomers) must be done effectively, easily, and reproducibly. As API is not batch testing each resin, their observations will be strictly qualitative. They will, in particular, comment on poor mixing of components, difficulty in reaction control (temperature, viscosity), difficulty in blending components, and poor mixing of resin components.

Each batch of MFA and resin manufactured by API will be batch tested by ARL/Drexel. The quality control of resin scale-up will be tested using a set of five tests as described in the JTP. ASTM D 1980-87 (11) will be used to access the acid number of MFA monomers and resins.

This test will determine if there is too much free acid remaining in the system, which would indicate incomplete conversion of the reactants into the MFA and VE monomers. FTIR testing, as described in La Scala et al. (4), will be used to determine the presence of unreacted epoxy groups. Unreacted epoxy groups indicate incomplete conversion of the reactants in the MFA and VE monomers. NMR, as described in La Scala et al. (7), will be used to determine various chemical aspects of the resins. First, the quantity of unreacted epoxy groups will be measured. The ratio of methacrylate groups to VE or MFA monomers will be quantified. Also, the molar ratio of VE to styrene in BMVE resins or VE/MFA/styrene in FAVE will be quantified. A rheometer will be used to measure the viscosity of the MFA monomers and low-HAP resins at 25 °C (4, 7). Too high of a viscosity indicates side reactions occurred that degrade the resin properties and processability. SEC, as described in La Scala et al. (7), will be used to determine the content of high molecular weight species in the MFA monomers, FAVE resins, and BMVE resins. Lastly, the gel time of the resin will be adjusted from 15 min to 4 h by varying the initiator, catalyst, and inhibitor contents. Being able to adequately adjust the gel time is important for creating parts of different sizes.

### **5.1.2 Neat Resin Testing**

Neat resin properties were assessed in a variety of laboratory tests to ensure quality of the resin prior to making composite parts. The FAVE resins should have properties similar to the incumbent resins. This testing is applicable to all demonstration/validation platforms.

Resin viscosity will be measured as described previously for measuring the MFA viscosity. Target viscosity was <1000 cP for all resins. The ability to control gel time will be measured by adjusting the initiator package to determine whether short, medium, and long gel times can be achieved. DMA will be used to assess the glass transition temperature of the neat resin polymers via the loss modulus maximum at 1 Hz with a deflection of 15 µm while ramping the temperature from 30 to 200 °C at a rate of 2 °C/min. Flexural testing according to ASTM D 790 M (13) will be performed to determine the modulus of elasticity and flexural strength. Three-point single-edge notch bend specimens are used for fracture toughness measurements according to ASTM 5045-93 (23).

### **5.1.3 Composite Panel Testing**

Selection of the fiber and resin systems for several DOD applications is summarized in table 8. Rectangular composite panels were prepared for the tests using samples that conform to the lay-up (type, number of plies, and thickness) (e.g., M35A3 hood, HMMWV hardtop) they are being used to validate.

Table 8. Proposed applications for commercial VE and FAVE composites in the military.

Application	Fabric	Resin	Resin Replacement
Amtech helmet hardtop	3-Tex 100-oz S2-glass and 24-oz S2-glass	Derakane 8084	FAVE-L-25S/O-25S
HMMWV hood	3-D E-glass	Hetron 980-35	FAVE-L-HT/O-HT
M35A3 and M939 hood	3-Tex 96-oz E-glass	Hetron 980-35 (VE) or Huntsman 8605 (Epoxy)	FAVE-L-HT/O-HT
Transmission container	3-Tex 54-oz E-glass	Derakane 8084	FAVE-L-25S/O-25S
T-38 dorsal cover and F22 canopy cover	Fibre glas developments corp. 120 3-oz E-glass and style 7781 E-glass 9 oz	Hexion 781-2140	FAVE-L-25S/O-25S
Rudders	Fiber glass ind. 18-oz E-glass	Corezyn Corve 8100 and Derakane 510A-40	FAVE-L-25S

The processing ability of the resin and mechanical properties of composite panels were tested to measure the performance requirements according to tables 3–7. As composite panels are being made for testing, the flow of resin through these panels was studied. Time for infusion was measured and compared to standard resins. In addition, the ability to gel when desired was measured. The composite panels were weathered using Xenon weathering, immersion in deionized water, salt water, JP-8, and methyl ethyl ketone. The composite properties were measured before and after exposure. The thermomechanical properties of composite samples were measured using DMA.

In order to evaluate tensile properties, a tensile test following ASTM D 638 (16) guidelines was performed. In order to evaluate compressive properties for Air Force composites, a compressive test following ASTM D 695 (17) guidelines was performed. Flexural strength and modulus were measured using ASTM D 790-92 (13). The interlaminar/short beam shear strength of each composite system was tested following ASTM D 2344-84 (14) for all demonstrations. For some applications, flexural strength and interlaminar strength were measured at room temperature and 250 °F to evaluate performance at elevated temperatures. The fiber, resin, and void fractions of the composites will be measured using ASTM 2584 (24).

Fatigue tests were run where the maximum displacement values were determined in correspondence to the maximum load of 80%, 60%, 40%—the load value obtained by the static flexural tests. The stress ratio  $R$ , a ratio of minimum and maximum load ( $\text{load}_{\min}/\text{load}_{\max}$ ), is a critical parameter that influences the fatigue behavior. Different  $R$  value scenarios can be identified as in the ISO standard ISO 13003 (25). The range of the  $R$  value for the flexural fatigue test can be 0–1, while 0.1 is commonly used. Ten thousand cycle tests were performed at a frequency of 1 Hz in order to minimize adiabatic heating effects as well as the time and cost of undertaking a fatigue program. After the fatigue tests, static flexural tests were given to each specimen to determine the residual flexural strength and elasticity modulus. Consequently, the

two samples can be compared under the same conditions. In this case, two specimens were tested for each design, and the values were averaged for the final results. Fatigue life was also determined for flexural loading conditions, where  $R = 0.5$ . These tests were conducted at a frequency of 4 Hz to reduce the test time, and 40% of the initial flexural load was applied to each test. After predetermined cycles, the residual flexural performance was measured.

## **5.2 Composite Part Validation Testing**

All composite part validation testing began with infusion trials. These were performed on mockup layups or full layups to determine whether the resin will successfully infuse the part. The actual infusions on full layups were performed. The ability of the resin to infuse the part was assessed by the manufacturer.

### **5.2.1 HMMWV Hardtop Demonstration/Validation Testing**

The Amtech hardtop has a few key material performance requirements that may be critical when changing resin systems. Potential issues were screened by doing sandwich testing—four-point bend (ASTM D 6272 [15]) and short beam shear testing (ASTM D 2344 [14]), as previously described. In addition, ballistic properties were measured, as previously described. Lastly, the ability of the part to endure vibrational loadings was measured by performing fatigue testing on composite samples.

### **5.2.2 Army Vehicle Hoods Demonstration/Validation Testing**

The truck hood had to be able to be manufactured via VARTM, and thus there were processing requirements. In addition, some basic properties had to be achieved in composite laminate coupons. Furthermore, the ability of the truck hood to withstand static load, cyclic load, high service temperatures, and impact was demonstrated to simulate the forces the structure would be exposed to in the field. A custom-designed and custom-built test fixture at the CCM (previously used to test the HMMWV and M35A3 hood designs) was used to validate the hood's performance (figure 5). The testing was performed on an M35A3 and M939 hood prepared from FAVE-L-HT, 8605 Huntsman epoxy, and Hetron 980/35. Army vehicle hoods were also tested for form, fit, and function at RRAD.

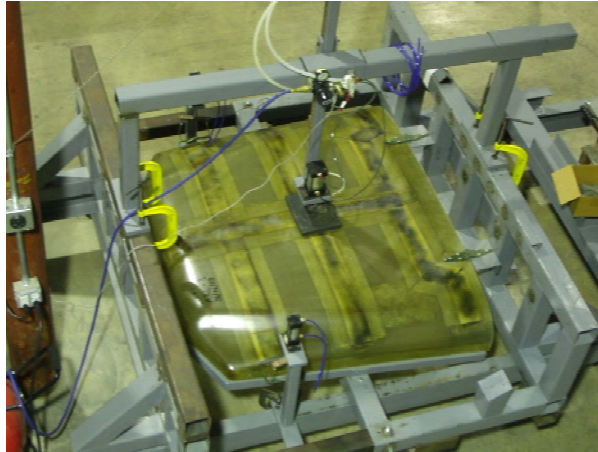


Figure 5. Center loading of M35A3 hood in test frame for static and cyclic testing.

In the static load experiments, a 250-lb weight was placed over a 3- × 3-in area at the center and front center of the hood to simulate a Soldier standing on the hood. A 250-lb load was applied to the outside surface over a maximum 10- × 10-in area. The load was applied at the center and front areas of the hood. The deflection was measured at the point of application of the load but on the opposite surface. The hood is required to deflect no more than 0.25 in at -50 °F and 0.5 in at 250 °F and sustain no damage. The durability requirement is for the hood to resist all damage from a 250-lb force downward at the center of the hood, followed by 100,000 cycles at 1 cps to simulate a cyclic soldier load on the hood for the lifetime of the vehicle. The flexural properties must be such that an upward force of 50 lbf at the right and left corners will not damage the part and not result in >0.5 in deflection. An upward load was applied at the corner lift handles. The center latch was engaged, and both right and left sides were tested (separately). Displacement of the hood corner above the fixture was measured. The structure must withstand cyclic corner loads. Fifty-pound upward loads were applied at the corner lift handles with the center latch engaged. The loads were applied in alternating fashion (right then left) over an 8-h period at 10 cycles per min. These tests simulated a lifetime of lifting the corners of the hood. The impact resistance was quantified by dropping a 2-lb chrome-plated steel ball with a 2 3/8-in diameter onto the hood from 6 ft. The ball was dropped on six different locations to ensure toughness across the structure, as only insignificant cosmetic damage was considered acceptable.

### 5.2.3 Army HMMWV Transmission Container Demonstration/Validation Testing

The properties of the HMMWV transmission containers were measured in the CCM and the Aberdeen Test Center (ATC) using established procedures. The edgewise test required dropping the fully loaded container on its edge from 18, 26, 29.5, and 37 in. Cornerwise testing required dropping the container on its corner from 18, 22, 29.5, and 34 in. The tip-over involved tipping the container onto its sides. The impact test involved swinging the container as a pendulum into a rigid wall. The flatwise drop involved dropping the container flatwise onto the feet from 15 and 30 cm. The stacking test involved stacking two containers onto each other and noting the

amount of slippage that occurred after tilting the containers 15° from the horizontal to either side. The concentrated load test involved placing 1800 lb on top of the containers for 16 h. The impact resistance test involved dropping a 2-lb ball onto the container from 6 ft on flat surfaces, small radius surfaces, and large radius surfaces. Furthermore, the container was tested against shock and vibration at ATC. Lastly, the container was validated in typical fielding conditions at RRAD.

The container was tested by ATC for vibration and loose cargo/shock testing in accordance with MIL-STD-810G (26) and A-A-52486 (27). The containers were also fielded at RRAD to assess their performance over a 3-month period.

#### **5.2.4 Air Force Demonstration/Validation Testing**

Processability is the primary test to qualify a resin for the T-38 dorsal cover, F-22 canopy cover, and splash mold applications after composite panel validation testing. Composite performance would be assessed in in-flight testing for the T-38 dorsal cover, which was not performed for this demonstration platform.

#### **5.2.5 Navy MCM Rudder Demonstration/Validation Testing**

Processability is a primary test to qualify a resin for this application after composite panel validation testing. The ability to flow across the part and wet out the part before gelation is extremely important. In addition, the part was sectioned to ensure good wetting of the fibers in the toes and in all areas of the part.

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## **6. Performance Assessment**

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### **6.1 JTP Results and Laboratory Results**

Initial batches of MFA and FAVE did not pass all JTP criteria. Modifications were made to the processes, which then resulted in passing performance on subsequent batches. API concluded that the MFA and FAVE resins are simply manufactured/produced and could be scaled-up easily.

Various resin formulations were prepared, including variants of each formulation to improve the resin performance (increase glass transition temperature [ $T_g$ ], reduce resin viscosity, or improve resin blending). All FAVE formulations were prepared using a commercial resin as the primary source of VE and styrene, while blending the resin with MFA.

A number of base formulations were determined a priori (table 9). In particular, these are the FAVE-L/O and FAVE-L/O-25S. The -HT formulations were defined only after it was determined that the -25S formulations did not meet the properties required for the Army hood applications. The basic formulations using 65 wt.% bisphenol A VEs only contained 20 wt.% styrene and 15 wt.% MFA (FAVE-L or FAVE-O) or 25 wt.% styrene and 10 wt.% MFA

(FAVE-L-25S and FAVE-O-25S). The basic formulations containing 65 wt.% Novolac and Bisphenol A VE with 25 wt.% styrene and 10 wt.% MFA are FAVE-L-HT and FAVE-O-HT.

Resin variants were created for each formula depending on the basis of the resin (e.g., Arapol 914 or Derakane 441-400) and the pure VE monomer used (e.g., CN-151 and RDX26936). The initial formulations for FAVE-L/O and FAVE-L/O-25S used Derakane 441-400 and CN-151 and were given the base name. The variants that used different components to make the same formulation were given extensions to signify the variant. For example, -RDX resins were formulated with Derakane 441-400 and RDX26936. -A1 resins used Arapol only as the VE component, while -A2 resins used Arapol 914 and Derakane 441-400. -VE formulation used only pure VE (RDX26936) for comparison purposes and was never manufactured at a significant scale. The properties of the ideal formulation of each resin and formulations used during the demonstration/validation are presented in table 10.

Table 9. Basic resin formulations.

Basic Formulation	Bisphenol VE (wt.%)	Bis A/Novolac VE (wt.%)	MLau (wt.%)	MOct (wt.%)	Styrene (wt.%)
FAVE-L	65	—	15	—	20
FAVE-O	65	—	—	15	20
FAVE-L-25S	65	—	10	—	25
FAVE-O-25S	65	—	—	10	25
FAVE-L-HT	—	65	10	—	25
FAVE-O-HT	—	65	—	10	25

Table 10. The formulations for the resin variants of FAVE-L and the neat resin properties. In bold are the optimum properties, and highlighted in green is the optimum formulation.

Component	FAVE-L	FAVE-L-A1	FAVE-O-A1	FAVE-L-25S	FAVE-L-25S-RDX	FAVE-L-25S-A1	FAVE-O-25S	FAVE-O-25S-A1	FAVE-O-HT	FAVE-L-HT-RDX	FAVE-O-HT-RDX
Derakane 441-400	60.6%			75.8%	75.8%		75.8%		75.8%	75.8%	75.8%
Derakane 470HT-400											
Arapol 914		<b>81.0%</b>	<b>81.0%</b>	14.2%		<b>81.0%</b>	14.2%	<b>81.0%</b>			
CN151	24.4%				14.2%				14.2%		
RDX26936										14.2%	14.2%
Styrene Added		<b>4.0%</b>	<b>4.0%</b>			<b>9.0%</b>		<b>9.0%</b>			
MLau	15.0%	<b>15.0%</b>		10.0%	10.0%	<b>10.0%</b>			10.0%		
MOct	15.0%	<b>15.0%</b>	<b>15.0%</b>				10.0%	<b>10.0%</b>	10.0%		10.0%
Viscosity at 25°C (cP)	900	<b>600</b>	<b>680</b>	550	550	360	550	<b>350</b>	530	560	530
Tg Dry (°C)	102	<b>120</b>	<b>122</b>	111	118	<b>125</b>	115	<b>128</b>	141	143	<b>144</b>
Tg Wet (°C)	91	<b>110</b>	<b>111</b>	101	110	<b>115</b>	104	<b>119</b>	131	133	<b>135</b>
Flex Mod (GPa)	2.7	<b>2.7</b>	<b>2.7</b>	2.9	2.9	<b>2.9</b>	2.9	<b>2.9</b>	2.8	2.8	2.8
Flex Str (MPa)	120	<b>120</b>	<b>120</b>	125	125	<b>125</b>	125	<b>125</b>	110	110	115
G <sub>IC</sub> (J/m <sup>2</sup> )	150	<b>190</b>	<b>180</b>	120	<b>200</b>	170	120	<b>165</b>	80	85	85

FAVE resin gel time was able to be adjusted to be as short as 5 min and as long as 4+ h. Furthermore, various initiator packages allowed for moderate gel times of 30–90 min.

The neat resin properties of the commercial resins are shown in table 11. The properties of the commercial resins are good with a combination of low viscosity and fairly high thermal properties. Compared to table 10, at least some FAVE resins have a viscosity, T<sub>g</sub>'s, flexural modulus, strength, and toughness similar to that of each commercial resin. Thus, a properly selected FAVE resin should meet the performance requirements for these demonstration articles.

Table 11. Properties of the commercial resins used in this work.

Resin	Viscosity (cP)	T <sub>g</sub> Dry (°C)	T <sub>g</sub> Wet (°C)	Flex Modulus (MPa)	Flex. Str. (GPa)	G <sub>IC</sub> (J/m <sup>2</sup> )
Corve 8100	200	128	119	3.0	125	150
Hexion 781-2140	300	130	121	3.0	130	160
Derakane 8084	600	115	103	2.8	120	650
Derakane 441-400	550	142	128	3.1	120	100
Hetron 980/35	500	130	119	3.0	120	150
Huntsman 8605	550	158	140	2.6	120	200

The properties of composite samples were measured. Fatigue results indicated that FAVE resins and commercial resins have very similar residual flexural strength and modulus. The spectrum of composite properties was also very similar for the FAVE resins relative to that of the commercial resins. Environmental aging results were also similar, except in a few cases (MEK aging) where the FAVE outperformed the commercial resins. Furthermore, the tests show that the FAVE composites have sufficient performance for each application. The results, which are too numerous to consolidate in this report, are listed in the final report.

## 6.2 Demonstration/Validation Results

### 6.2.1 Air Force Demonstration/Validation

The flow of FAVE resins were compared to that of the Hexion 781-2140 incumbent resin. This was performed by preparing connected or identical rectangular fiber layups and infusing FAVE resin into one layup and the Hexion resin into the other (figure 6). The results clearly showed that the FAVE-L resin was much more viscous than the Hexion resin and took significantly longer to infuse the part. FAVE-L-25S also took slightly longer to infuse the part, but the time difference was much less.

For the T-38 dorsal cover, the major issue with the FAVE-L resin was that the viscosity does not match the commercial resin that is diluted with the styrene monomer. This resulted in a lower inflow rate and a longer processing time to infuse the fiber pack. The infusion of the part per process specifications was unsuccessful due to the higher viscosity of the FAVE-L resin system. The FAVE-L resin gelled (cured to a rapid jump in viscosity) before the fiber pack was completely infused (figure 6).





Figure 6. Top left: splash mold resin flow test. Top right: failed attempt to infuse T-38 dorsal cover with FAVE-L. Bottom left: final F-22 canopy cover being fit tested on an F-22. Bottom right: splash mold after removal from aircraft surface.

There were no major issues encountered during the process of using the FAVE-L-25S to make the F-22 canopy cover (figure 6). The FAVE-L-25S resin performed very well, and the ACO was able to fully infuse the canopy cover. The fit testing at both Hill and Elmendorf Air Force Bases was successful. By performing permeability tests on the FAVE-L-25S resin, we were able to design an infusion system that would ensure complete wet-out before gelation of the resin. With this system, we were able to successfully infuse the canopy cover with the FAVE-L-25S resin system, using our designed process on the first attempt. No process changes had to be made to accommodate the FAVE-L-25S resin system, and it compared equally to other commercial VE resin systems used for infusion. The part met the criteria of being manufactured in less than a day. It also had the strength and stiffness requirements for two maintenance workers to transport, install, and uninstall the cover. This part validates that the FAVE-L-25S resin system can be used successfully to perform a VARTM infusion of a large-scale part.

Once all the fabric was placed on the surface, the splash mold layup was covered and sealed with a nylon vacuum bag. Vacuum was drawn on the part, and the infusion process was started after the resin was ready. We used 2000 g of FAVE-L-25S resin to infuse the part. From the total resin weight, 0.15% of Cobalt Naphthenate was used as the promoter, and 1.0% of methyl ethyl

ketone peroxide was used as the activator. It took 30 min to fully infuse the part, and 60 min for the part to gel. After infusion, the part was allowed to cure at room temperature for 24 h and was then removed from the surface of the horizontal stabilizer. The part was cleaned up and inspected for cracks or surface abnormalities. No cracks or abnormalities were found (figure 6).

There were no issues encountered when using the FAVE-L-25S resin to infuse the rapid splash mold. The resin performed adequately as compared to other resins with similar viscosity. The slightly higher viscosity of the FAVE-L-25S resin, due to the lack of styrene, did not have a negative effect on the infusion of the part. The splash mold made with the FAVE-L-25S resin maintained surface shape and held vacuum integrity in order to successfully create a repair part. The FAVE-L-25S resin was validated during the rapid splash molding process against the criteria the ACO specified for the program. The resin was successfully infused against the surface of the aircraft to create a splash with the size and thickness required. After being built, it held vacuum to enable fabrication of a repair part off of the splash tool. During the process no cracks or abnormalities appeared in the surface of the splash tool made by the FAVE-L-25S resin system. The FAVE-L-25S resin performed adequately compared to higher styrene content VE resin systems.

### **6.2.2 Navy MCM Composite Rudder**

The FAVE-L-25S resin was used in place of the Corve 8100 resin to manufacture the MCM composite rudder. The gel time was modified from short to very long (6 h) for various initiator packages used. In addition, flow studies showed good infusion capability of the resin, similar to that of Derakane 510A, a resin commonly used by the Navy.

Two composite rudders were manufactured by SCI in a variety of steps. In general, the face sheet infusions took ~1 h to infuse through the vertical height of the rudder. Initially there was concern that the nominally higher viscosity of the FAVE-L-25S resin (400 cps) compared to the CORVE 8100 resin (100 cps) would cause problems with the infusion, but the infusions were fairly well behaved. The resulting rudder is shown in figure 7. The slight wrinkling is a result of the process, not the resin itself. One of the rudders was cross sectioned (figure 7). The results showed excellent fiber wet-out and low void content, similar to that of the rudder previously made using the Corve 8100.

### **6.2.3 HMMWV Transmission Container**

The HMMWV transmission container was demonstrated in the laboratory and then at SMC. Both the CCM and SMC were pleased with the performance of the resin regarding infusion of the part. The resin took ~30 min to fully infuse the part, and no dry fibers or defects were visible. The final FAVE HMMWV transmission containers had the same overall quality as the Derakane 8084 containers (figure 8). Both resins processed very similarly. Thus, according to SMC, the FAVE resin is a viable alternative to the Derakane 8084.



Figure 7. Completed MCM rudder one showing leading edge (left), side view (top right), and cross section of leading edge near the caul plate (bottom right).



Figure 8. Photograph of the inside of completed laboratory demonstrated HMMWV transmission container (left) and assembled FAVE HMMWV transmission container manufactured by SMC (right).

The transmission containers were validated using lab testing, ATC shock and vibration testing, and field testing at RRAD. The FAVE and Derakane containers passed all laboratory validation testing, including the impact test, cornerwise drop test, etc. Both sets of containers passed most aspects of RRAD field and ATC vibration and shock testing. The wooden feet and some aspects of the aluminum hardware failed during both tests (figure 9). Fortunately, the composite parts themselves performed very well, showing that the FAVE-L-25S is a suitable candidate to replace



Figure 9. Top left: photograph showing the broken wooden feet after loose cargo testing. Bottom left: evidence of corner impact—local crushing but still holding together. Right: transmission fluid bled into core.

Derakane 8084 for this application. The laboratory validation tests were performed after the field tests and showed that the containers still passed all performance requirements, and the FAVE-L-25S container performed as well as the Derakane container. Thus, the FAVE-L-25S is sufficient for the HMMWV transmission container application.

#### **6.2.4 M35A3 and M939 Hoods**

Both the CCM and SMC were pleased with the performance of the resin regarding infusion of the parts. The resin took ~50 min to fully infuse the part, and no dry fibers or defects were visible. The final FAVE hoods had the same overall quality as the Hetron 980/35 and Huntsman 8605 hoods (figure 10). The FAVE-L-HT and resins processed very similarly as well. Thus, according to SMC, the FAVE-L-HT is a viable alternative to the baseline resins.

The hoods were validated on the CCM test rig. The results showed the FAVE hoods passed the required specification by wide margins. Furthermore, the hoods performed nearly identically to that of the hoods made using the commercial resins. The hoods were attached to M35A3 and M939 trucks to test form, fit, and function. RRAD was able to simply attach these hoods to M35A3 trucks. The resulting hood fit onto the truck body very well. The hood had sufficient clearance with the engine block and withstood the forces of people standing and jumping on it.





Figure 10. Topside of FAVE-L-HT-RDX M35A3 hood (left) manufactured by SMC and the underside of FAVE-O-HT-RDX M939 hood (right) manufactured by the CCM.

### 6.2.5 Marines HMMWV Hardtop

The 4-ply panel was tested against a National Institute of Justice (NIJ) IIIa (44 magnum) equivalent. The 12-ply panel was tested against NIJ III (7.62 M80 ball) equivalent. The results clearly showed that all three FAVE resins outperformed the Derakane 8084 and performed similarly to the ballistic FCS2 epoxy resin. Fatigue testing and the loose cargo testing done for the HMMWV hood using the FAVE-L-25S resin showed that FAVE-L-25S would be a good resin choice for the HMMWV hardtop.

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## 7. Cost Assessment

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A life cycle analysis (LCA) was performed on the FAVE resins relative to that of the commercial resins for each composite part demonstrated/validated in this work. Two independent sources (Concurrent Technology Corporation [CTC] and Steven Smith of Drexel University) were used to perform the LCA to eliminate bias as much as possible and to hopefully come to a more accurate conclusion.

The cost of the MFA monomers and FAVE resins was estimated by examining the costs of the components and the operational costs to react and blend the components. The cost was then estimated assuming a 25% and 40% markup. The estimated price of the MFA ranged from \$1.23 to \$2.85/lb according to Drexel, depending on the production scale and whether MLau or MOct was produced (MLau is cheaper than MOct). The price of MLau was estimated as \$2.91/lb, and MOct should be priced at \$4.38/lb according to CTC. The price of the FAVE resins ranged from \$2.01 to \$4.38/lb, depending primarily on the production scale and secondarily on which resin formulation was made. Table 12 lists the most likely resin price from each analysis. The commercial resins ranged in cost from \$2.0 to \$13.27/lb.

Table 12. Estimated price of FAVE resins and the estimated cost avoidance using the FAVE resins vs. the commercial resins for the most likely scenario.

Part	Baseline Resin	Baseline Resin Price/lb (Drexel)	Baseline Resin Price/lb (CTC)	FAVE Resin	FAVE Resin Price/lb (Drexel)	FAVE Resin Price/lb (CTC)	Cost Avoidance /lb (Drexel)	Cost Avoidance /lb (CTC)	Net LCA Savings /lb (Drexel)	Net LCA Savings /lb (CTC)
HMMWV transmission containers	Derakane 8084	\$3.0/lb	\$3.43	FAVE-L-25S	\$3.09–\$3.88	\$3.13	\$1.13	\$0.34	\$0.25–\$1.04	\$0.21
M939/M35A3 Hood	Hetron 980/35 Huntsman 8605	\$2.75 \$10	\$2.36 \$13.27	FAVE-L-HT	\$3.57–\$4.33	\$3.73	\$1.13 0	\$0.34 0	\$0.31/ –\$0.45 \$5.67–6.43	–\$1.03 \$9.54
HMMWV hardtop	Derakane 8084	\$3.0	\$3.43	FAVE-L-25S	\$3.09–\$3.88	\$3.13	\$1.13	\$0.34	\$0.25–\$1.04	\$0.21
Air Force parts	Hexion 781-2140	\$2.50	\$2.49	FAVE-L-25S	\$3.09–\$3.88	\$3.13	\$1.13	\$0.34	\$0.49/ –\$0.26	–\$0.30
MCM Rudder	Corve 8100	\$2.40	\$2.00	FAVE-L-25S	\$3.09–\$3.88	\$3.13	\$1.13	\$0.34	\$0.44/ –\$0.35	–\$0.79

Note: Green indicates a positive life cycle analysis (LCA), yellow indicates negative LCA coupled with positive LCA, and red indicates only a negative LCA for the FAVE resin.

The cost difference in emissions controls and monitoring for the commercial resins vs. the FAVE resins was calculated by sizing the regenerative thermal oxidizers to accommodate the production rate of each part individually and all together (more likely to represent a typical manufacturer's composite production rates). Table 12 shows the cost avoidance for using FAVE resins in place of the commercial resins for a typical manufacturing setting (large-scale composite production). Some applications have a positive LCA for the FAVE resins (HMMWV transmission container, HMMWV hardtop), some are borderline (M939/M35A3 hoods), and some appear to favor the current commercial resins (Air Force parts and MCM rudder). Table 13 shows the cost and cost savings per part based on the life cycle for the FAVE resin relative to commercial resins. The trends are the same as for table 12.

The shelf life of FAVE resins was found to be 10% greater than that of styrenated resins. Currently, 5%–10% of resins are disposed of due to exceeding shelf life. Thus, the cost savings associated with increased shelf life is 1% of the baseline resin cost, which is \$0.02–\$0.034/lb for VE resins and \$0.13/lb for epoxy resins.

Table 13. Cost and savings per composite part for FAVE resins relative to commercial resins based on CTC cost estimate only.

Part	Baseline Resin Cost/Part	FAVE Resin Cost/Part	Net LCA Savings/Part
HMMWV transmission containers	\$138.52	\$115.03–\$162.07	\$23.49/–\$23.54
M939 hood	\$61.59 (VE), \$291.94 (epoxy)	\$82.06–\$116.16	–\$20.47/–\$54.57 \$209.88/\$175.78
M35A3 hood	\$55.43 (VE), \$262.75 (epoxy)	\$73.85–\$104.54	–\$118.9/–\$158.21 \$209.88/\$175.78
HMMWV hardtop	\$912.34	\$757.46–\$1067.22	\$154.88/–\$154.88
Air Force parts	\$12.68	\$14.02–\$19.76	–\$1.34/–\$7.08
MCM rudder	\$466.83	\$624.44–\$879.80	–\$157.61/–\$412.97

Note: Green indicates a positive life cycle analysis (LCA), yellow indicates negative LCA coupled with positive LCA, and red indicates only a negative LCA for the FAVE resin.

## 8. Implementation Issues

The production of FAVE resins is in transition. Dixie Chemicals, Inc., has recently licensed the MFA and FAVE technology from Drexel University. As a result of this, API is no longer allowed to manufacture the MFA or FAVE, except at the behest of Dixie Chemicals. Dixie Chemicals is in the process of scaling up the MFA technology and is looking for industrial partners (Ashland, etc.) to manufacture the FAVE resin. Until these steps are accomplished, the production of the resin will be limited. Although mass production of FAVE by Dixie Chemicals or its partners cannot be guaranteed, there is a good chance that it will be produced in a 1–3 year time frame.

The HMMWV transmission container demonstration/validation showed that the design of the container must be modified to meet Army specifications. The required changes are low risk. In particular, the failure of the wooden feet for this container indicates the need for more expensive feet. This will, in turn, make the container more expensive and could limit its demand. Regardless, RRAD was very happy with the performance of container, which they considered far superior to past solutions. Thus, overall, we expect the risk of this implementation issue to be low.

Since the start of this project, the M3A3 truck has been discontinued from military use. Therefore, implementation of the M35A3 truck hood will not happen. Nonetheless, other hoods, such as the M939, have a need for composite solutions, which could be implemented using FAVE resins. However, implementation of these other hoods, including the M939, will take a while because there are no approved technical data packages for these parts. These technical data packages are in the approval process, but past experience has shown that this will take 2–3 years. The risk of implementing the FAVE resins for Army truck hood applications is low but will be delayed.

The T-38 dorsal cover application is being supported by a military contractor on an as-needed basis. Despite that, it is possible that they will use the FAVE resin for this application. However, they are currently using UPE resins because of their lower cost and will not likely switch to the more expensive FAVE resins for this application. The splash molds are controlled by the ACO. The ACO was satisfied with the performance of the FAVE resins and thus will use these resins when they are available for this application. The ACO was also satisfied with the use of the FAVE resins for the F-22 canopy cover. Again, they will use the FAVE resins when they are made available again. Furthermore, the ACO will likely use the FAVE resins for all relevant VE applications because of the good performance of these resins.

The MCM composite rudder performed well according to NSWCCD and Structural Composites. However, the rudder was prepared in a manner different from the previous rudder, as it used a composite internals rather than bronze internals. This decreased the cost of the part significantly. Nonetheless, the new design must be approved. Furthermore, although the FAVE resin performed well, some properties were different from the commercial resin. As a result, the new design and resin would have to be qualified. Implementation of new parts on Navy ships is a long process. Although we expect that the resin/composite meets the performance needs, we expect the implementation delays to be significant (~5 yr). Furthermore, LCA did not favor the more expensive FAVE resins. Manufacturing these resins through a larger company that could possibly drive the price even lower would increase implementation probability. Thus, the risk associated with implementing the FAVE resins on MCM and other rudders is high.



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## List of Symbols, Abbreviations, and Acronyms

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ACO	Advanced Composites Office at Hill Air Force Base
AD	areal density
AFB	Air Force Base
AFRL	U.S. Air Force Research Laboratory
APG	Aberdeen Proving Ground
API	Applied Poleramics, Inc.
ARL	U.S. Army Research Laboratory
ASTM	American Society for Testing and Materials
ATC	Aberdeen Test Center
BMVE	bimodal vinyl ester resin system
CCM	center for composite materials
CTC	Concurrent Technology Corporation
DDG	current class of Navy destroyer
DDX	future class of Navy destroyer
DMA	dynamic mechanical analysis
DOD	U.S. Department of Defense
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FAVE	fatty acid vinyl ester resin system
FAVE-L	fatty acid vinyl ester resin system based on lauric acid
FAVE-O	fatty acid vinyl ester resin system based on octanoic acid
FTIR	Fourier transform infrared spectroscopy
G <sub>IC</sub>	mode 1 fracture energy/toughness
HAP	hazardous air pollutant

HMMWV	high-mobility multiwheeled vehicle
JTP	joint test protocol
LCA	life cycle analysis
MCM	mine-countermeasure ship
MFA	methacrylated fatty acid
MLau	methacrylated lauric acid
MOct	methacrylated octanoic acid
MW	molecular weight
NESHAP	National Emissions Standard for Hazardous Air Pollutants
NIJ	National Institute of Justice
NMR	nuclear magnetic resonance spectroscopy
NSWCCD	Naval Surface Warfare Center Carderock
RRAD	Red River Army Depot
SBS	short-beam shear
SCI	Structural Composites, Inc.
SEC	Size Exclusion Chromatography
SMC	Sioux Manufacturing Corporation
T <sub>g</sub>	glass transition temperature
UPE	unsaturated polyester
VARTM	vacuum-assisted resin transfer molding
VE	vinyl ester
VOC	volatile organic compound

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